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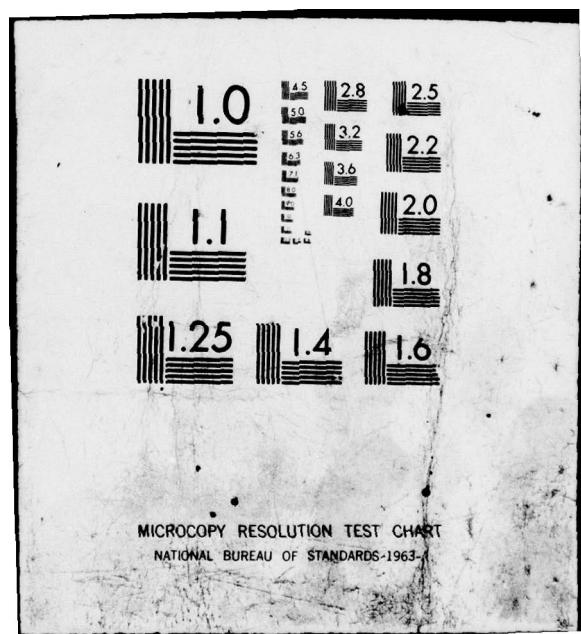
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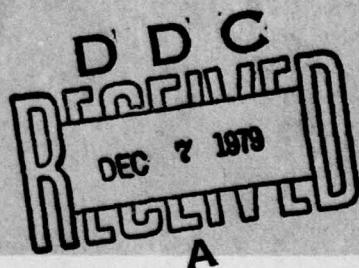
Coil Spring Failures in Aerospace Hardware

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8 November 1979

Interim Report

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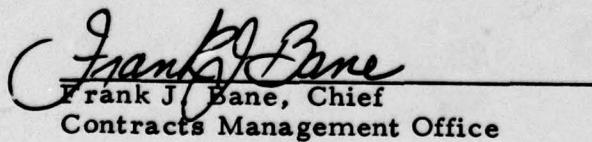
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Gerhard E. Aichinger
Project Officer

FOR THE COMMANDER



Frank J. Bane
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I. INTRODUCTION

Mechanical springs are used in a variety of applications in aerospace systems where both efficiency and reliability are required. Typical applications include the control of switching characteristics of miniature switches and the deployment of missile fairing panels, where spring rates of hundreds of pounds per inch are required.

Because of its versatile and well-understood characteristics, the common helical cylindrical coil spring has become the preferred choice for many applications. However, failures that have occurred during life testing of cyclic-loaded miniature extension springs and during the use of sustain-loaded compression springs in aerospace hardware are evidence that reliability problems frequently arise with these springs. The failure of these springs has been studied and the sources of the reliability problems identified.

II. SMALL EXTENSION SPRINGS

The results of life testing of cyclic-loaded, miniature, extension springs have revealed that the end hooks of these springs are a major source of weakness.

In one set of springs, failures frequently occurred at the base of the end hooks after a few hundred thousand load cycles. These springs, made from 0.02-in.-diam 17-7 PH stainless steel wire, were age-hardened at 900°F for 1 hr (CH 900 condition) after coiling and then chemically treated to produce a black oxide coating. (For 0.02-in.-diam wire, the CH 900 condition provides an ultimate tensile strength in excess of 320,000 psi.¹ This high strength is the result of extensive cold-working prior to aging.)

In an effort to determine the reason why some springs are susceptible to premature failure, the metallurgical condition of the spring material was investigated. The only abnormalities found by means of a metallurgical analysis of a failed spring were a roughened surface of the spring wire and a concentration of microstructural damage at the base of the end hooks.

The surface roughness varied along the circumference of the wire (Fig. 1). This surface condition was attributed to a mild chemical attack that was a result of the black oxide coating treatment. The microstructural damage, which was concentrated at the base of an end hook, is shown in Fig. 2 as many radial cracks on the end coil that forms the base of the end hook. Similar damage was found on the opposite end hook of the same spring.

An identical spring that survived the life test was examined and found to have the same surface roughness as the failed spring. No microstructural

¹ Corrosion Resistant Steel Wire, 17Cr-7Ni-1A1 Precipitation Hardening - Spring Temper, ASM 5673, Aeronautical Material Specifications, New York (1975).

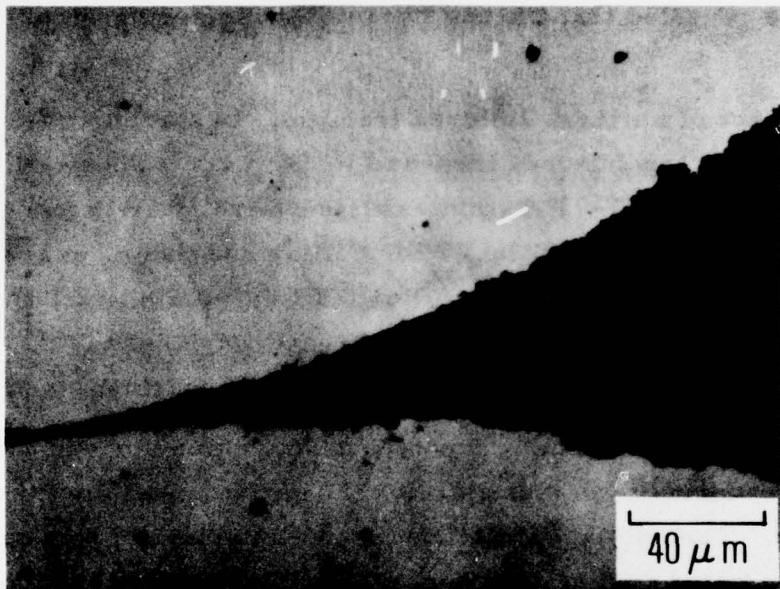


Figure 1. As-Polished Cross-Sectional View of Two Adjacent Coils on a Spring Subjected to a Black Oxide Coating Treatment. Typically, the exposed surface of the wire was rough, whereas unexposed areas near the crevice between adjacent coils were comparatively smooth.

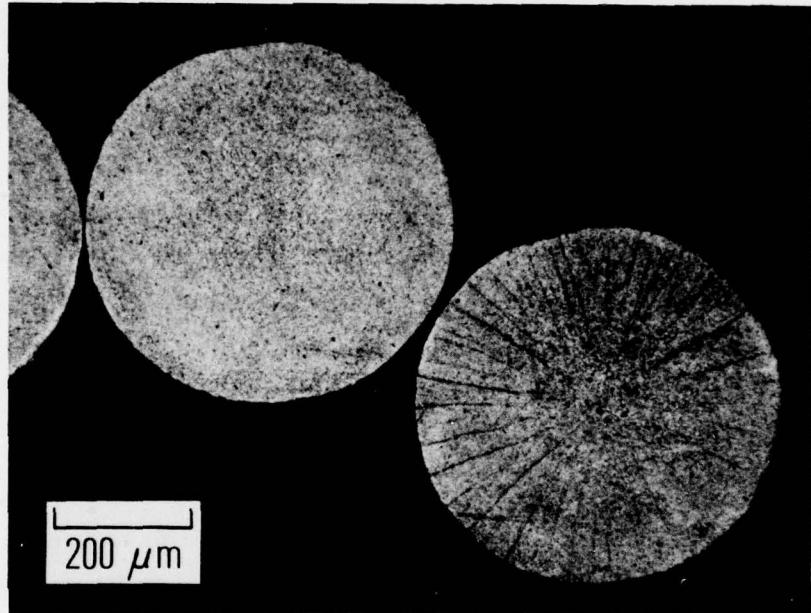


Figure 2. Polished and Etched Cross-Sectional View of the Coils Adjacent to an End Hook of a Failed Spring. Numerous radial cracks were confined to the end coil (on the right) forming the base of the end hook. Similar cracks were found concentrated at the base of the opposing end hook on the same spring. Etched with Marbles Reagent.

damage, however, was detected at the base of the end hooks on the unfailed spring.

The radial crack pattern at the base of an end hook on the failed spring (Fig. 2) strongly resembles the type of damage caused by torsional fatigue in shafts.² This indicates that the torsional stresses were concentrated in this area of the end hooks. Thus, the source of the stress concentration was investigated.

A concentration of torsional shear stress that results from the geometry of the bend at the base of the end hook is identified in MIL-STD-29A, a commonly used mechanical spring design standard.³ The severity of the stress concentration depends on the sharpness of the bend (i.e., the ratio of r_2 to r_4 , Fig. 3). Variations in end hook arrangement, however, but not in end hook bend radii, correlated with fatigue damage at the base of the end hooks.

The design standard does not consider how the end hook stresses are affected by variations in end hook arrangement. Limits on the amount of variation in end hook arrangement are recommended, however, and these limits must be considered important to spring reliability. Unfortunately, these limits concern spring size (Fig. 4) and are not mandatory requirements. Consequently, as spring size decreases, these limits become increasingly difficult to maintain and, therefore, less likely to be adhered to. Thus, for small springs, where variations in end hook arrangement can be a significant part of the spring dimensions, the manner in which this arrangement affects the end hook stresses must be considered for the sake of reliability.

²"Fractography and Atlas of Fractographs," Metals Handbook, Vol. 9, American Society for Metals, Novelty, Ohio (1975), p. 43.

³Drawing Requirements for Mechanical Springs, MIL-STD-29A, U.S. Dept. of Defense (1962), p. 83.

Torsional Stress S_t at Section A'

$$S_t = \frac{16 PR}{\pi d^3} \times \frac{r_2}{r_4}$$

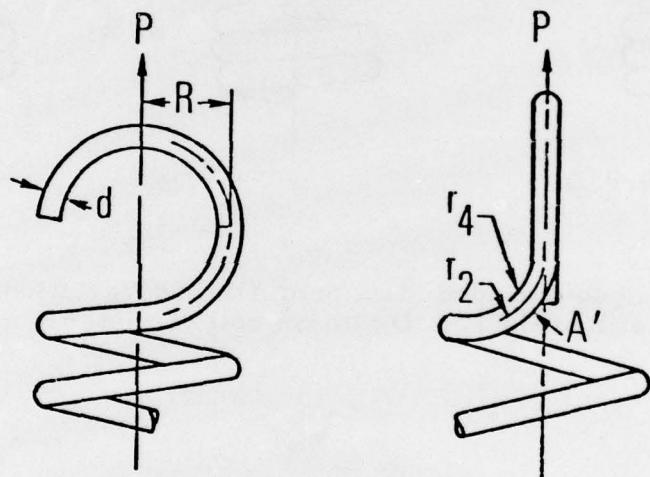


Figure 3. Stress Concentration at the Base of an End Hook Due to End Hook Geometry

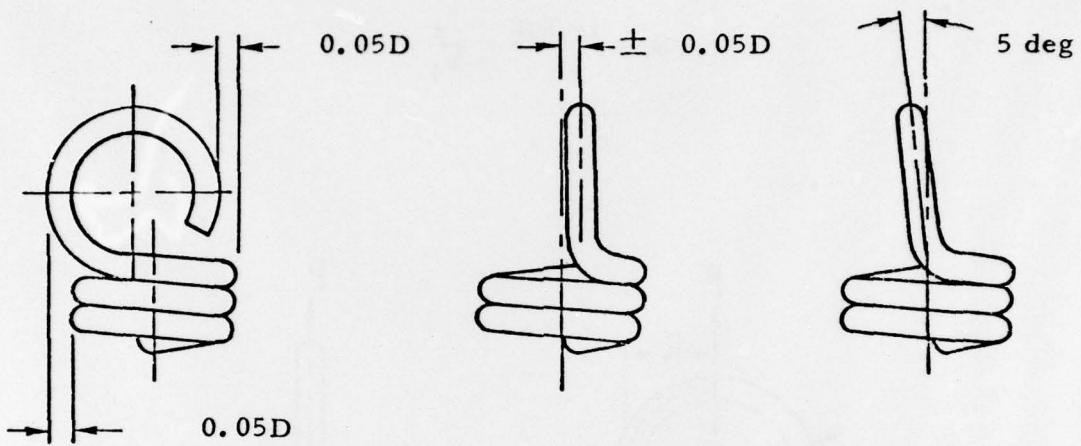


Figure 4. Recommended Maximum Allowed Variation in Alignment of End Hooks. D = mean coil diameter.

In other small extension springs, of slightly different configuration, fatigue failures occurred over a large range of load cycles and were confined to an area of the end hook midway between the base and top of the end hook. These springs were made from 0.01-in.-diam AISI 302 Condition B stainless-steel wire and were stress-relieved at 550° F prior to testing. Condition B is the spring temper designation. This spring temper produces, by means of cold-working, a tensile strength in excess of 320 ksi for a 0.010-in.-diam. wire.⁴

Examination of several failed springs revealed that, in each case, a fatigue crack developed approximately midway through the cross-sectional area of an end hook before complete failure occurred. A typical fracture surface is shown in Fig. 5. The flat, generally featureless area on the fracture surface corresponds to the fatigue-cracked area, whereas the highly textured, dimpled area opposite the fatigue region corresponds to material pulled apart by a single application of load. For each failure examined, a fatigue crack origin could be associated with either tool marks on the end hook (Fig. 6) or with a rough surface (Fig. 7).

As with the previous set of 17-7PH springs, the generally poor quality of the surface of the AISI 302 spring wire was at first suspected to be responsible for the variable fatigue performance of the springs. As in the previous case, however, examination of a spring that survived life testing showed that it had essentially the same surface defects as the failed springs. Thus, as determined before, some variable other than surface quality had to be affecting fatigue life.

Examination of the end hooks of several untested springs indicated that the end hook configuration varied considerably from spring to spring. Since the end hooks of these springs were made to fit closely over a loading pin, an interference fit was possible. Although end hook stresses from

⁴Corrosion Resisting Steel Wire, QQ-W-423B, U.S. General Services Administration (1969).

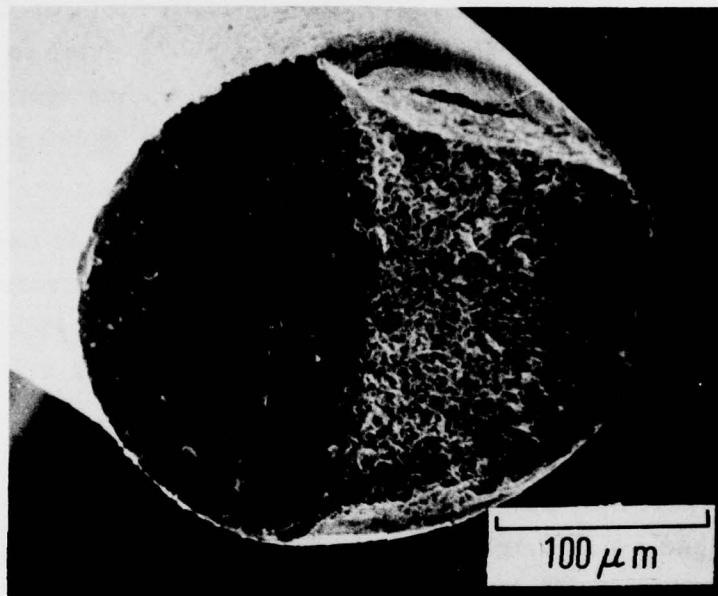


Figure 5. Typical Appearance of the Fracture Surface
on End Hooks of Cyclic-Loaded Miniature
Extension Springs Made from 0.010-in.-
-diam AISI 302 Stainless Steel Wire

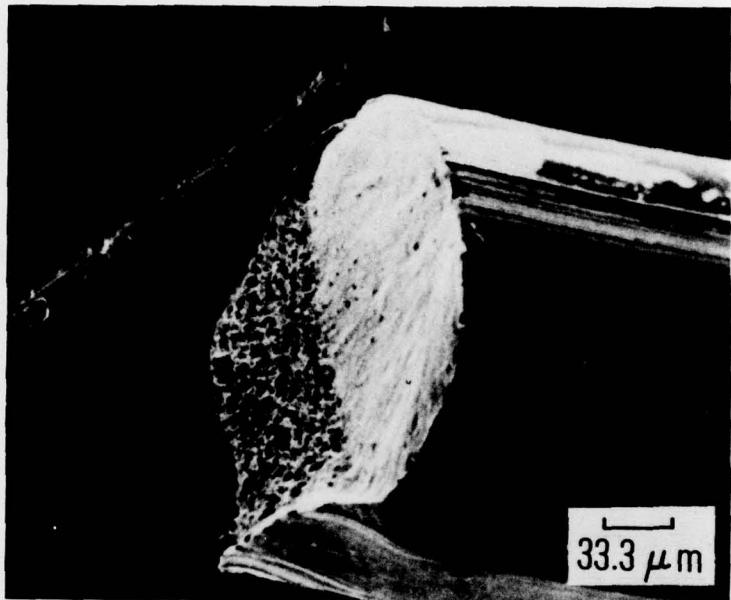


Figure 6. Tool Marks Found on the End Hooks
of Failed AISI 302 Springs

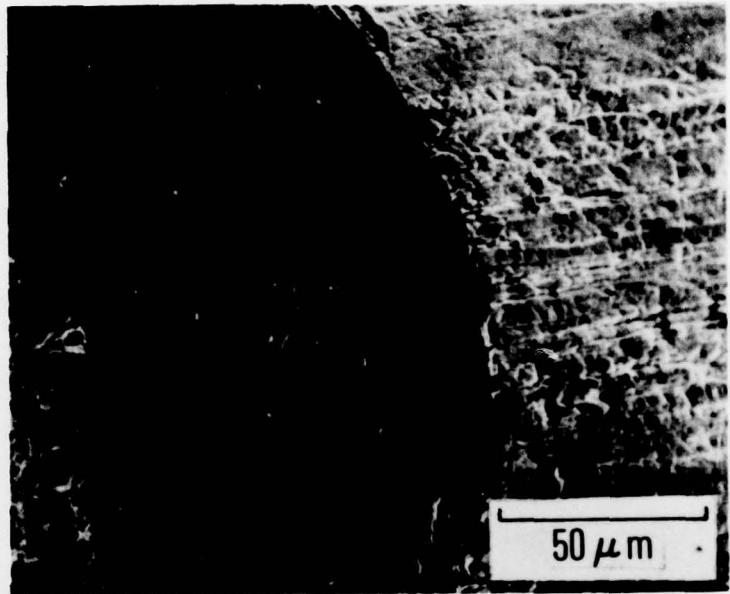


Figure 7. Surface Roughness Associated with Fatigue Crack Origin on Failed AISI 302 Stainless Steel Springs

interference fits are not considered in MIL-STD-29A, they are important to spring reliability if large stresses are likely to develop.

Bending stresses from interference fits were estimated by the method given in the Appendix. In Fig. 8, the interference stress is plotted as a function of the interference for two different end hook diameters. This plot demonstrates that, for a given interference fit, the bending stress from interference increases rapidly as spring size (i.e., end hook diameter) decreases. Obviously, interference fits are to be avoided in the end hooks of small springs.

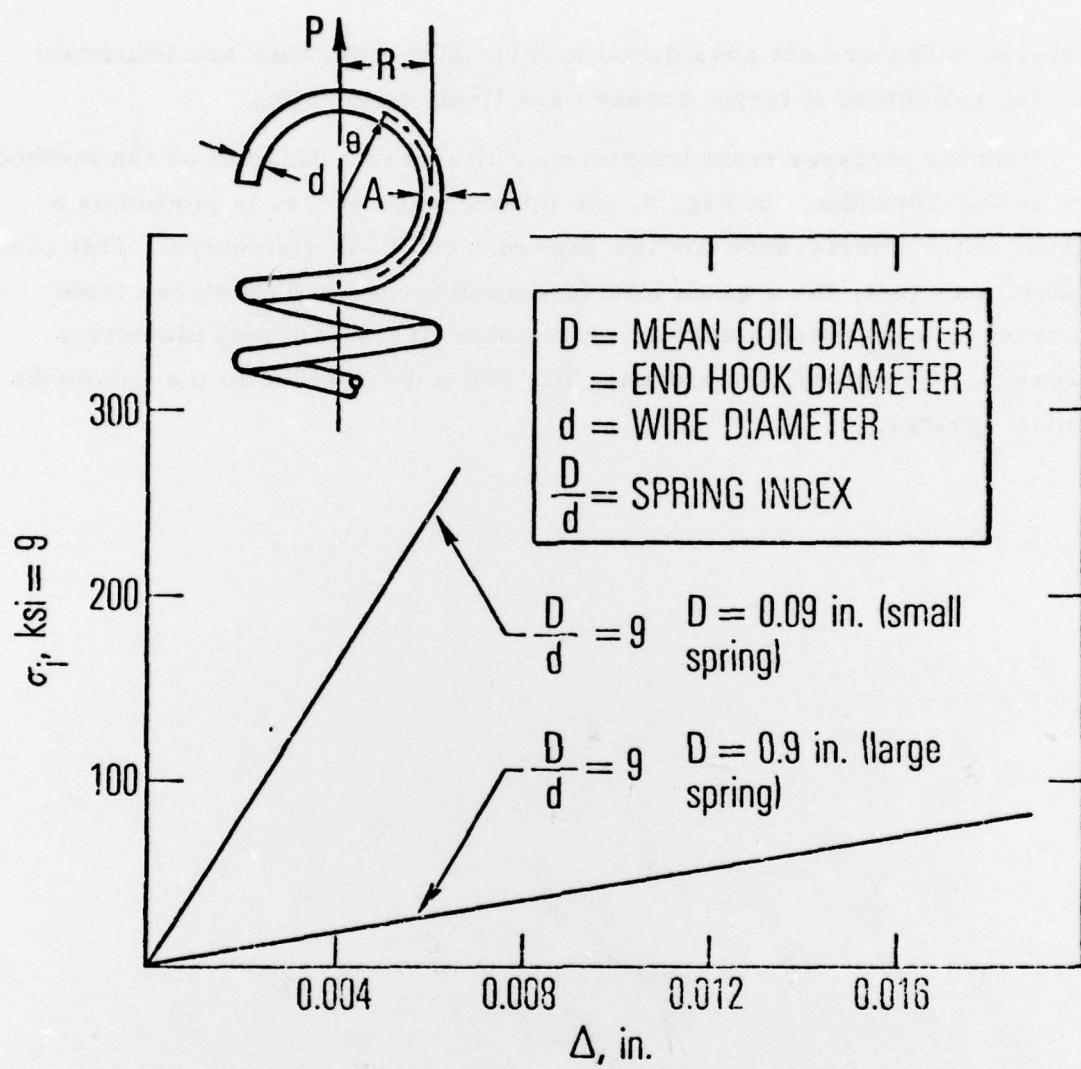


Figure 8. Interference Stress σ_i at Critical Section of End Hooks vs Interference Fit Δ . σ_i determined from Eq. (A-2) in the Appendix.

III. STRESS-CORROSION PROPERTIES

Results of stress-corrosion testing of the 17-7 PH CH 900 and Custom 455 CH 850 stainless steels indicated a need for careful consideration of the stress-corrosion properties of candidate materials for spring applications. For 0.18-in.-diam 17-7PH wire, the CH 900 condition produces an ultimate tensile strength between 254 and 284 ksi by cold-working and age-hardening at 900°F for 1 hr.¹ For 0.18-in.-diam Custom 455 wire, the CH 850 condition produces an ultimate tensile strength between 260 and 290 ksi by cold-working and age-hardening at 850°F for 1/2 hr.⁵

Results of early laboratory testing of these two materials indicated that Custom 455 was somewhat more resistant to stress corrosion than the 17-7 PH spring material. Thus, the Custom 455 material was selected for several sets of compression springs for use in deployment of missile fairing panels. Results of life testing by exposure to a sea coast environment for several months indicated that these springs satisfied the reliability requirements. Because of a subsequent service failure of one of the Custom 455 compression springs, however, which was attributed to stress corrosion, a second, more detailed, examination of the stress-corrosion properties of these two materials was carried out.

Differences in corrosion properties and stress-corrosion resistance of the two materials in the form of age-hardened wire (hardness = R_c 47 to 49, wire diameter = 0.18-in.) were not obvious. The corrosion properties were similar:

1. Neither material was corroded by short-term exposure (up to 20 days) to salt water (3-1/2%).
2. Both materials were mildly corroded by saturated salt water (25% NaCl).

⁵Carpenter Custom 455 Technical Bulletin, Carpenter Technology Corporation, Reading, Pennsylvania (1971), p. 23.

3. Both materials were readily corroded by simulated galvanic coupling (in 3-1/2% salt water) to slightly more noble materials.

The stress-corrosion resistances were also similar: both materials developed stress-corrosion cracks in short time periods when simultaneously exposed to corrosive conditions and loaded in bending to stresses below their yield strength.

From these results, neither material could be determined to be superior in terms of resistance to stress-corrosion cracking. There were, however, obvious differences in the direction of stress-corrosion paths between the two materials. In the 17-7PH spring wire (loaded in bending as shown in Fig. 9), cracking was confined to a longitudinal plane running parallel with the wire axis. This cracking path persisted even when a deeply notched sample was stress corroded (Fig. 10). In the Custom 455 spring wire (similarly loaded in bending), cracking developed across the wire at an angle of approximately 30 deg to the wire axis. The cracking paths on unnotched samples of the materials are compared in Fig. 11.

The difference in cracking paths is significant in consideration of how applied stresses are distributed in the coil wires of sustain-loaded springs. When a coil spring is compressed (or extended), the coil wires essentially are loaded in torsion. Under torsional loads, pure shear stresses develop along planes parallel and perpendicular to the wire axis, and pure normal (i.e., tensile) stresses develop along planes 45 deg to the wire axis. Since stress-corrosion cracking requires the existence of tensile stresses,⁶ such cracking under torsional loads would not be expected to develop along planes parallel or perpendicular to the wire axis. Failures reported in the literature indicate that this is the case.⁷

⁶E. N. Pugh, "On the Mechanism(s) of Stress-Corrosion Cracking," A. R. C. Westwood, ed., Metallurgical Society Conferences, Gordon and Breach, New York (1965), p. 354.

⁷"Failure Analysis and Prevention," Metals Handbook, Vol. 10, American Society for Metals, Novelty, Ohio (1975) pp. 487-499.

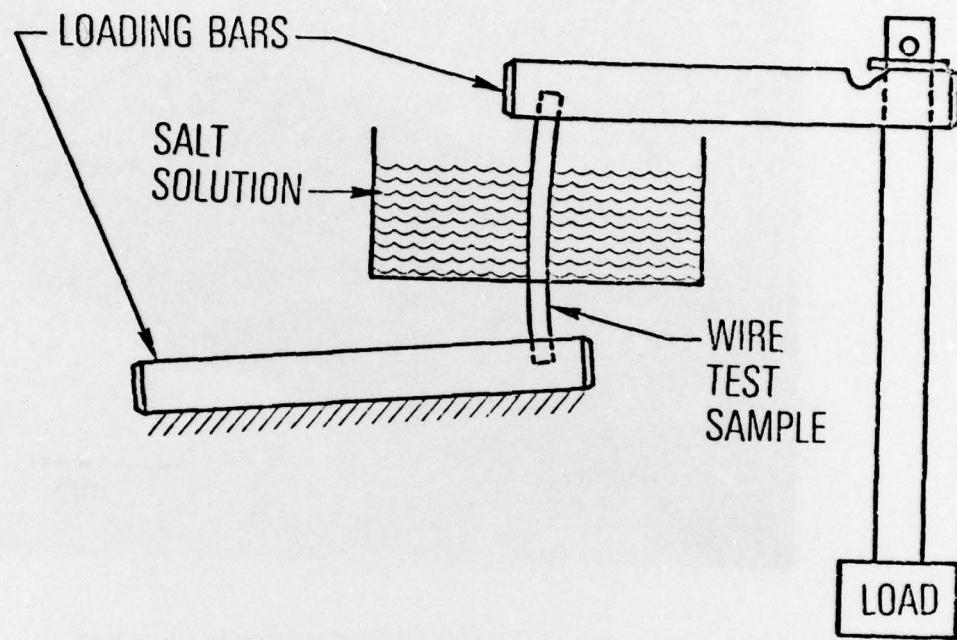


Figure 9. Fixture for Sustained Load Bending of Wire

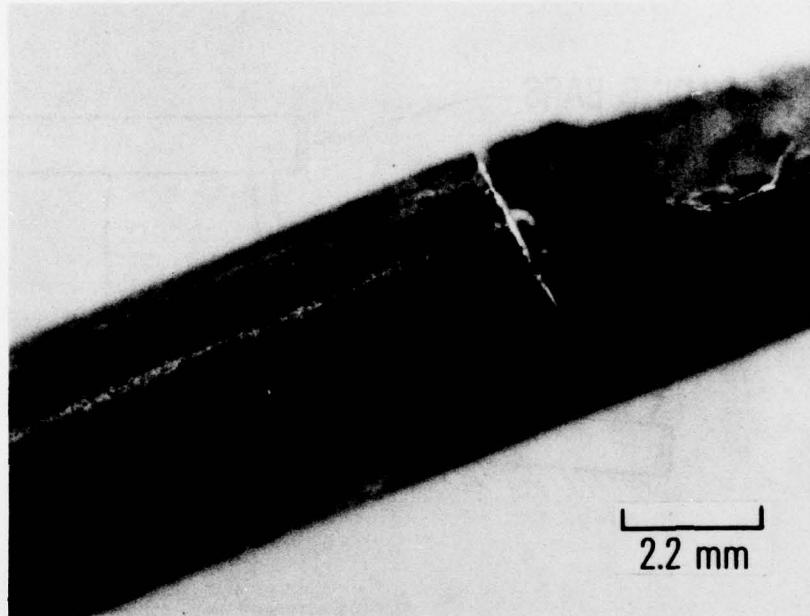


Figure 10. Stress Corrosion Cracks in Notched 17-7 PH Spring Wire, Loaded in Bending. Cracks developed parallel to the wire axis on both sides of the notch

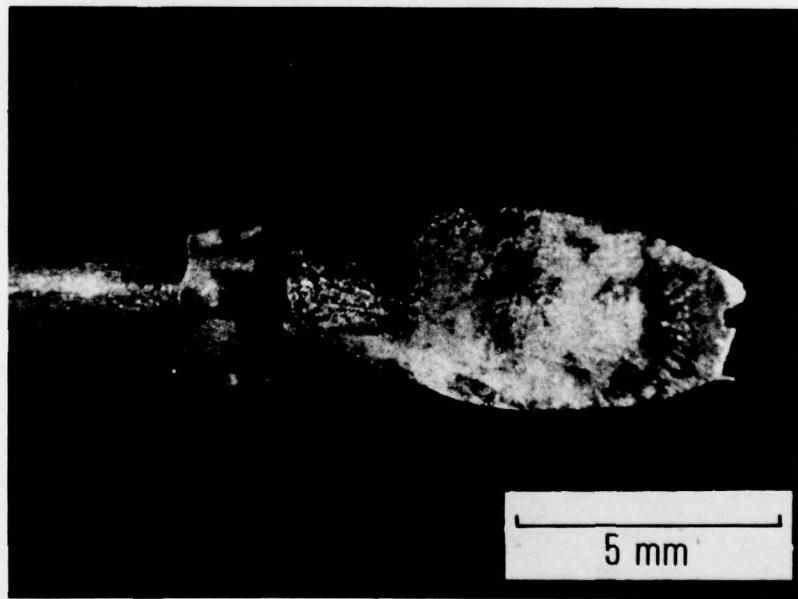
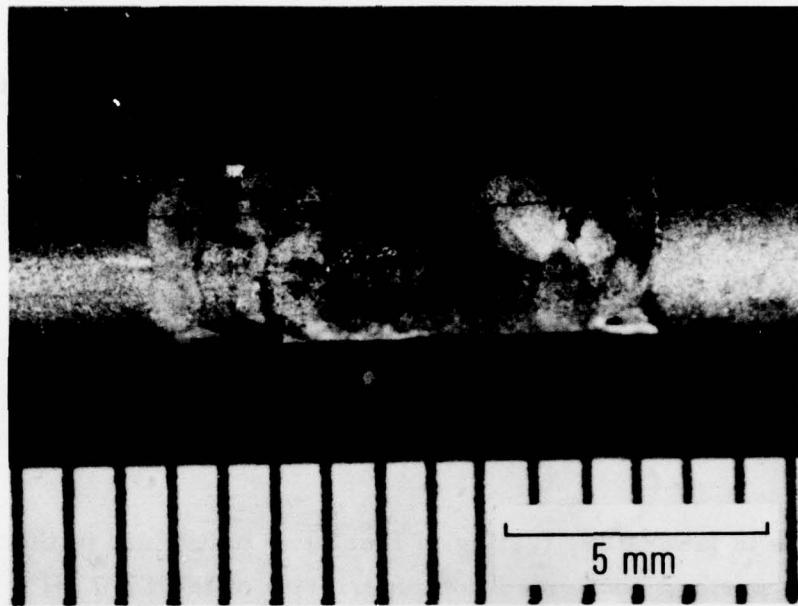


Figure 11. Stress Corrosion Crack Paths in 17-7 PH, CH 900 Wire (upper) and in Custom 455, CH 850 wire (lower). Both samples were loaded in bending and are shown with the tensile side up.

Since the 17-7PH, CH 900 spring material was susceptible to stress corrosion only along a longitudinal plane, and this plane is subject to little or no applied tensile stresses under torsional loads, the 17-7PH, CH 900 wire would be expected to be resistant to stress corrosion when used in a coil compression spring. As stress-corrosion cracking in the Custom 455 wire tended to follow a path only a few degrees from the plane of maximum tensile stress under torsional loading, its resistance to stress corrosion would not be expected to vary significantly when incorporated into a coil spring.

Results of laboratory testing of these two materials in the form of compression springs confirmed the superiority of the 17-7PH material over the Custom 455 material. It should be emphasized, however, that this rating of the stress-corrosion superiority of the 17-7PH material over the Custom 455 material applies only to wire material, and then only when normal (tensile) stresses are not present in planes longitudinal to the wire axis. Thus, this rating would not be applicable to extension springs, where normal stresses in the end hooks can develop across a longitudinal plane.

APPENDIX

METHOD FOR ESTIMATING BENDING STRESS AT CRITICAL SECTION IN END HOOK DERIVED FROM INTERFERENCE FIT*

With it assumed that interference produces a deflection Δ at the top of the end hook, deflection can be related to a bending moment M acting on the end hook with the use of the virtual work method of strength of materials

$$\Delta = \int_0^\pi \left(\frac{M}{EI} \right) \left(\frac{\partial M}{\partial P} \right) R d\theta$$

where $M = PR \sin \theta$, and $\partial M / \partial P = R \sin \theta$ (Fig. 8).

Then, by direct substitution

$$\begin{aligned}\Delta &= \int_0^\pi \left(\frac{PR \sin \theta}{EI} \right) (R \sin \theta) R d\theta \\ &= \frac{R^3 P}{EI} \int_0^\pi \sin^2 \theta d\theta \\ &= \frac{R^3 P}{EI} \left[\frac{\pi}{2} \right]\end{aligned}$$

When the equation is arranged to obtain the equivalent force P at the top of the end hook

$$P = \frac{2EI\Delta}{\pi R^3} \quad (A-1)$$

*Richard Chang, private communication (1978).

The bending stress at the critical section (A-A) can now be determined from the flexure formula

$$\sigma_i = \frac{MC}{I}$$

where $M = PR$, $R = D/2$, and $C = d/2$

Thus,

$$\sigma_i = \frac{P(D/2)(d/2)}{I}$$

and with P , from Eq. (A-1) substituted

$$\sigma_i = \frac{2EI\Delta}{\pi(D/2)^3 I} \left(\frac{D}{2}\right) \left(\frac{d}{2}\right)$$

which reduces to

$$\sigma_i = \frac{2E\Delta d}{\pi D^2} \quad (A-2)$$

Thus, the interference stress varies inversely with the square of the end hook diameter, i.e., with spring size, since end hook diameter is generally equal to the coil diameter.

LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space and missile systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

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